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Author: Ms. Robyn Natherson
University of Colorado Boulder, United States

Prof. Daniel Scheeres
Colorado Center for Astrodynamics Research, University of Colorado, United States

ROBUST MISSED THRUST DESIGN UTILIZING REACHABLE SETS

Abstract

Advances in low-thrust propulsion technology enable long duration spaceflight at significantly reduced fuel costs. This allows humanity to fly missions with larger payloads to farther destinations, while responsibly utilizing Earth's scarce resources. However, low-thrust spacecraft require significantly longer thrust arcs compared to those with conventional chemical propulsion systems. Burn durations can span days, weeks, or even months. These extended thrusting periods increase the likelihood that a spacecraft anomaly will overlap with a planned burn, causing the spacecraft to deviate from its nominal trajectory. This is referred to as the *missed thrust problem*. Without robust trajectory design, losses from missed thrust events jeopardize mission objectives, especially when flight paths include encounters with celestial bodies. In this work, we present a strategy to design robust transfers accounting for missed thrust by leveraging reachability results.

Reachability results can be formulated in two ways, forwards and backwards. This work specifically utilizes backwards reachable sets, or controllable sets. Controllable sets characterize the region of full-state initial conditions which can reach a target within a finite time. Typically, designing for missed thrust involves an iterative process where candidate transfers are tested for robustness and updated until design constraints are satisfied. However, applying reachability theory to study the missed thrust problem allows the entire solution space to be studied at once, avoiding this tedious process. One notable robustness metric is the missed thrust recovery margin (MTRM). The MTRM is the amount of time a spacecraft can coast away from a nominal trajectory before the target becomes inaccessible. Computing the MTRM for points sampled on the controllable set enables us to determine allowable coast lengths for a specified arrival time. We compute this quantity in our reachability framework by propagating points forward in time and recording when they exit the controllable set. We then design trajectories to fly through regions known to have the desired MTRM by visualizing this metric in phase space with a heatmap.

Low-thrust propulsion enables deep space exploration at a fraction of the fuel cost. However, due to the missed thrust problem, robust design strategies are integral for promoting mission assurance for flight projects employing low-thrust systems. Using the MTRM to map regions in phase space where transfers are resilient to thruster outages, our novel reachability-informed trajectory design approach changes how to view the missed thrust problem.